# MEASUREMENT REPRODUCIBILITY AND SENSOR PLACEMENT CONSIDERATIONS IN DESIGNING A WEARABLE PULSE OXIMETER FOR MILITARY APPLICATIONS

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*Abstract*- **Reproducibility of physiological measurements and the selection of suitable sensor locations are essential design criteria for developing a wearable pulse oximeter. In this paper we investigate the reproducibility of measuring arterial oxygen saturation ($SpO_2$) from a reflectance pulse oximeter sensor incorporated into an army helmet. Simultaneous measurements acquired from the forehead, chin, jaw and nape areas showed that the forehead region provides the best anatomical location for obtaining reproducible readings compared to other feasible helmet-mounted sensor locations.**

## I. INTRODUCTION

The interest in telemedicine for monitoring soldiers during combat situations has risen significantly in recent years. Despite the importance of monitoring the physiological status of soldiers during training or on the battlefield, we believe that currently there are no acceptable wearable telesensors that meet the stringent requirements for combat applications.

Ling, et al [3] noted that most warfare injuries sustained by soldiers were localized to the extremities. Additionally, although attractive, it is challenging to develop a reliable wearable physiological sensor that can be mounted on the hand or wrist without impeding a soldier's ability to use a firearm effectively or conversely without having the sensor's reading affected by routine combat activities. Thus, it remains questionable whether the use of a conventional transmission type finger pulse oximeter is suitable for combat applications. Recently, we showed that the head region provides an alternative and convenient site for monitoring $SpO_2$ by a reflectance pulse oximeter [1].

Commercially available reflectance-type pulse oximeter sensors are typically attached to the skin using a double-sided disposable adhesive tape. While this method of sensor attachment is acceptable for clinical applications, it poses practical constraints in military applications since soldiers wearing such a sensor may operate in hot or humid environments. Additionally, sweat could compromise the integrity of the adhesive tape, and therefore, the ability to maintain proper sensor attachment for extended periods of time.

To avoid the need to rely on using adhesive tape, we investigated an alternative sensor attachment technique by utilizing the existing helmet suspension liner, adjustable harness, and chin strap to keep the sensor in direct contact with the skin. Tests were performed in our laboratory to assess whether measurement reproducibility might be affected when the helmet is removed and repositioned without adjustments by the subject.

## II. METHODOLOGY

### *Experimental setup*

A military Kevlar helmet was equipped with four identical reflectance mode sensors (Nonin Medical, Inc., Plymouth, MN) in order to monitor $SpO_2$ from the forehead, nape, upper jaw and chin, as depicted in Fig. 1. Two sensors were mounted on an adjustable slide that was affixed to the inner front and inner back sides of the helmet in order to account for different head sizes and shapes. The other two sensors were embedded into the chin and jaw straps. As shown in Fig. 2, the four Nonin reflectance sensors were connected to Xpod® pulse oximeters and a Nellcor (Nellcor, Inc., Pleasanton, CA) transmission mode sensor was attached to the left index finger of a volunteer serving as a control. Data were acquired by a laptop PC via a RS232 serial port hub. Data from the transmission pulse oximeter was captured by another PC through a National Instruments DAQ card controlled by LabVIEW v.6.0 software. $SpO_2$ measurements were acquired at a rate of 3 samples per second. The two PCs were synchronized using time stamps to facilitate data analysis.

**Figure 1.** Strategic sensor locations used for data collection.

### *Experiments*

Two 23-year old healthy male volunteers were fitted with a standard army helmet while sitting comfortably in a resting position. Initially, the helmet restraining straps were adjusted by each subject to keep the sensors in close contact with the skin. Following a short period of rest, and before $SpO_2$ data were acquired, we confirmed that the readings were stable and the heart rate values displayed by all five pulse oximeters remained within 1%.

Initially, baseline measurements were acquired by instructing the subject to remain still for 3 minutes. Each subject was then instructed to remove the helmet and after 30 seconds reposition the helmet on the head without readjusting the straps. Each set of measurements were acquired twice in succession.

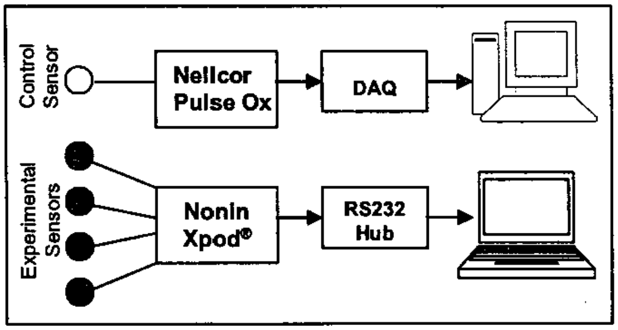


**Figure 2.** Experimental setup used for data collection

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III. Results

Typical $SpO_2$ values obtained from all five sensors in one trial are shown in Fig. 3. Table 1 summarizes the results of the statistical data analysis plotted in Fig. 3 by averaging two consecutive trials on the same subject. Based on the calculated bias values (0.19 ± 0.83) using the finger sensor as a reference, we found that readings acquired from the forehead were the most accurate compared with measurements obtained from other locations that we tested in this study.

Fig. 4 shows the reproducibility in measuring $SpO_2$ from the forehead following two successive 30-second periods while the helmet was removed from the subject's head.

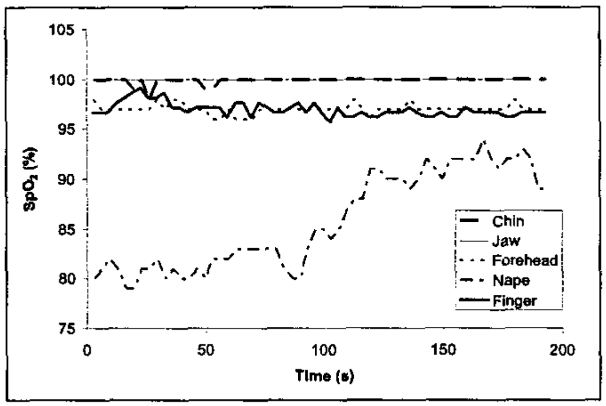


**Figure 3.** Comparison of $SpO_2$ readings for one trial obtained from four sensor locations with readings obtained simultaneously from a finger sensor serving as a control.

**Table 1.** Statistical analysis of four experimental sensor locations for two trials plotted in Fig 3.

| Location | Data Points (N) | Bias (%) | Std. Dev. (%) |
|---|---|---|---|
| Forehead | 1000 | 0.19 | 0.83 |
| Chin | 1000 | 3.17 | 0.70 |
| Jaw | 1000 | 3.17 | 0.69 |
| Neck | 1000 | -14.68 | 5.44 |

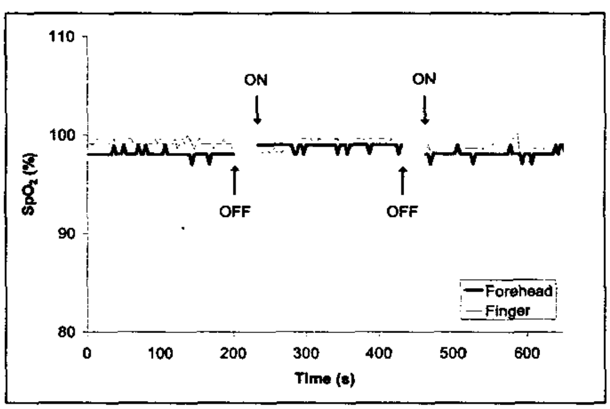


**Figure 4.** $SpO_2$ measurements from the forehead sensor. Arrows indicate when the helmet was removed and 30 seconds later repositioned on one subject.

IV. Discussion

Sensor placement and measurement reproducibility are perhaps the two most important factors to consider in designing a wearable pulse oximeter for future military applications.

Among the sites tested in this study, we found that the nape region could be problematic in obtaining accurate and reproducible measurements of $SpO_2$. Conversely, we also found that compared with the finger, $SpO_2$ measurements acquired from the forehead had the smallest bias and were most reproducible compared to the other anatomical locations selected on the head. Analysis of the data recorded from the forehead revealed that a 95% confidence limit include inaccuracies ranging between -1.44% and 1.83%. These inaccuracies are within a ±3% error typically considered acceptable for clinical practice [4].

From the data plotted in Fig. 4 we determined that the largest deviations found between the forehead and finger readings were less than 2%. Similar differences were previously noted by Pujary [2]. We believe that these discrepancies are acceptable given the fact that two different types of pulse oximeters were compared.

Further studies are underway to test the effect of motion artifacts on measurements obtained from a similar arrangement of helmet-mounted sensors. We envision that by focusing our future efforts on the selection of suitable sensor attachment techniques that would minimize inaccuracies due to motion artifacts, it is possible to develop a more robust method for monitoring $SpO_2$ that would satisfy the stringent requirements for adopting wireless physiological monitoring utilizing pulse oximetry in future military applications.

V. Conclusion

Preliminary data presented in this paper confirmed that it is possible to achieve adequate reproducibly by measuring $SpO_2$ and pulse rate from a helmet-mounted reflectance type pulse oximeter sensor without the need to use adhesive tape to secure the sensor on the skin or readjustment of the helmet straps between successive measurements. Although discernable PPG signals can be detected from the nape region, we found that the photoplethysmographic signals measured by the reflectance sensor are generally too weak and would result in large and clinically unacceptable measurement errors.

Acknowledgement

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